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# Broadband upconversion imaging around 4 $\mu\text{m}$ using an all-fiber supercontinuum source

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## ABSTRACT

We present a novel mid-infrared imaging system born from the combination of an all-fiber mid-IR supercontinuum source developed at NKT with ultra-sensitive upconversion detection technology from DTU Fotonik. The source delivers 100 mW of average power and its spectrum extends up to 4.5  $\mu\text{m}$ . The infrared signal is passed through a sample and then focused into a bulk AgGaS<sub>2</sub> crystal and subsequently mixed with a synchronous mixing signal at 1550 nm extracted from the pump laser of the supercontinuum. Through sum frequency generation, an upconverted signal ranging from 1030 nm to 1155 nm is generated and acquired using an InGaAs camera.

**Keywords:** Infrared imaging, Upconversion, Optical systems and sensors, Supercontinuum

## 1. INTRODUCTION

Mid-infrared spectroscopy and imaging have been receiving much attention over the last decade<sup>1</sup> because many chemical compounds have clear identifiable fundamental absorption lines in the mid-infrared (mid-IR) wavelength region. Usually, mid-IR detectors operate using low band-gap semiconductor materials like indium antimonide (InSb) or mercury cadmium telluride (HgCdTe). Alternatively, microbolometer arrays and thermopiles can also be used. However, these detectors suffer from inherent dark noise and require cooling to perform optimally.<sup>2</sup> Additionally, these detection systems are usually very expensive. The combination of high brightness mid-IR supercontinuum lasers and upconversion detection systems opens a unique possibility of combining two leading-edge technologies, pointing towards extremely fast and/or extremely sensitive imaging and spectroscopy in the mid-IR range. Supercontinuum sources are the brightest broadband light sources available today which makes them a powerful tool to analyze a wide range of samples.<sup>3</sup> Upconversion detection circumvents the usual complications of mid-IR detection by translating the mid-IR signal to the near-infrared (near-IR) wavelength region by nonlinear parametric sum-frequency mixing in a  $\chi^{(2)}$  medium. The upconverted signal can thus be detected using an affordable silicon or InGaAs based CCD array operating in the near-IR region. These detectors are known to work with much better noise and time performance than their counterparts in the mid-IR.<sup>4</sup>

In recent years, much research effort has been focused on upconversion detection both for imaging and spectroscopy using either bulk or waveguide structures in the nonlinear material. Pulsed upconversion has been demonstrated and successfully used for spectroscopy applications.<sup>5</sup> Broadband illumination in an intracavity upconversion setup has been shown to enhance the angular field of view.<sup>6</sup> Also, hyperspectral image reconstruction has been achieved using an intracavity upconversion imaging system in conjunction with a broadband thermal source.<sup>7</sup> Lastly, pulsed upconversion imaging between 2  $\mu\text{m}$  and 2.6  $\mu\text{m}$  using a supercontinuum source has been reported.<sup>8</sup>

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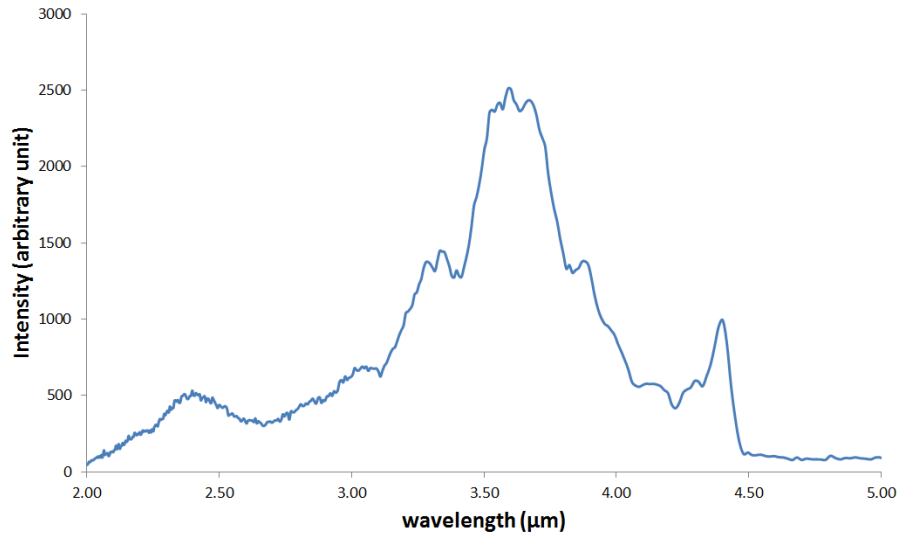


Figure 1: Spectrum of the supercontinuum source. The intensity is represented on a linear scale.

## 2. EXPERIMENTAL SETUP

In this paper, we rely on the high brightness of an IR supercontinuum source to build what, to our knowledge, is the first single-pass pulsed upconversion imaging system based on supercontinuum in the 4  $\mu\text{m}$  wavelength region. This system has the special feature of relying on the same pump laser to synchronously generate both the broadband signal pulse and the pump pulse for the nonlinear mixing process. This eliminates both the need for a second laser and ensures the perfect temporal overlap of the supercontinuum and conversion pump pulses.

The high peak power of the conversion pump pulses ensures the upconversion of the IR signal and suppresses the need for an intracavity setup. A single-pass setup with synchronous pumping<sup>5</sup> relaxes the demanding constraints for the nonlinear material to have high nonlinearity and low transmission losses. This allows the use of bulk crystals which can easily be manufactured in sizes of the order of several mm, which allows for the use of a large beam diameter in the nonlinear crystal, thus increasing spatial and spectral resolution.

The pulsed nature of the mixing laser will improve the signal to noise ratio of the system by eliminating the upconversion of background between signal pulses. As the duty cycle of the laser is approximately 1:10000, the pulsed upconversion can reduce the impact of upconverted background light by up to 40 dB.

In our experiment, the source relies on a 1550 nm erbium fiber-laser delivering 3.5 ns pulses at 40 kHz as pump source. The pulse is then separated into two arms with a 90/10 fiber coupler. The higher power pulse is made to propagate through a combination of standard single-mode silica fibers and a section of passive thulium-doped fiber followed by a section of ZBLAN fiber used to generate a supercontinuum ranging from 1.8  $\mu\text{m}$  to 4.5  $\mu\text{m}$  with an average power of approximately 100 mW.<sup>3</sup> The lower power pulse is propagated through a standard single-mode silica fiber of the same length as the high power arm so that the two pulses will be synchronized at the outputs of the source. The 1550 nm pulse will be used as the mixing pump in the upconversion process. The raw spectrum of the supercontinuum can be seen in Fig. 1.

The synchronized supercontinuum and mixing pulses are delivered to the setup through two separate fibers as indicated in Fig. 2. Both the supercontinuum and the mixing laser are randomly polarized. The supercontinuum light is first filtered with a 2  $\mu\text{m}$  long-pass filter. The filtering is necessary to prevent direct detection of the shorter wavelengths of the supercontinuum on the InGaAs camera. After this filter, the supercontinuum spans from 2  $\mu\text{m}$  to 4.5  $\mu\text{m}$ . The supercontinuum is then collimated to a 14.9 mm diameter beam using a 50.8 mm focal length 30° off axis parabolic mirror (OAPM), and then shone through the sample plane. The sample plane is transformed by a 25.4 mm focal length 30 OAPM to create a two-dimensional Fourier transform of the samples transmission in the nonlinear crystal.<sup>9</sup> This plane will be referred to as the Fourier plane. It is of interest to note that the use of OAPMs allows for an achromatic system, capable of operating with good performance across a

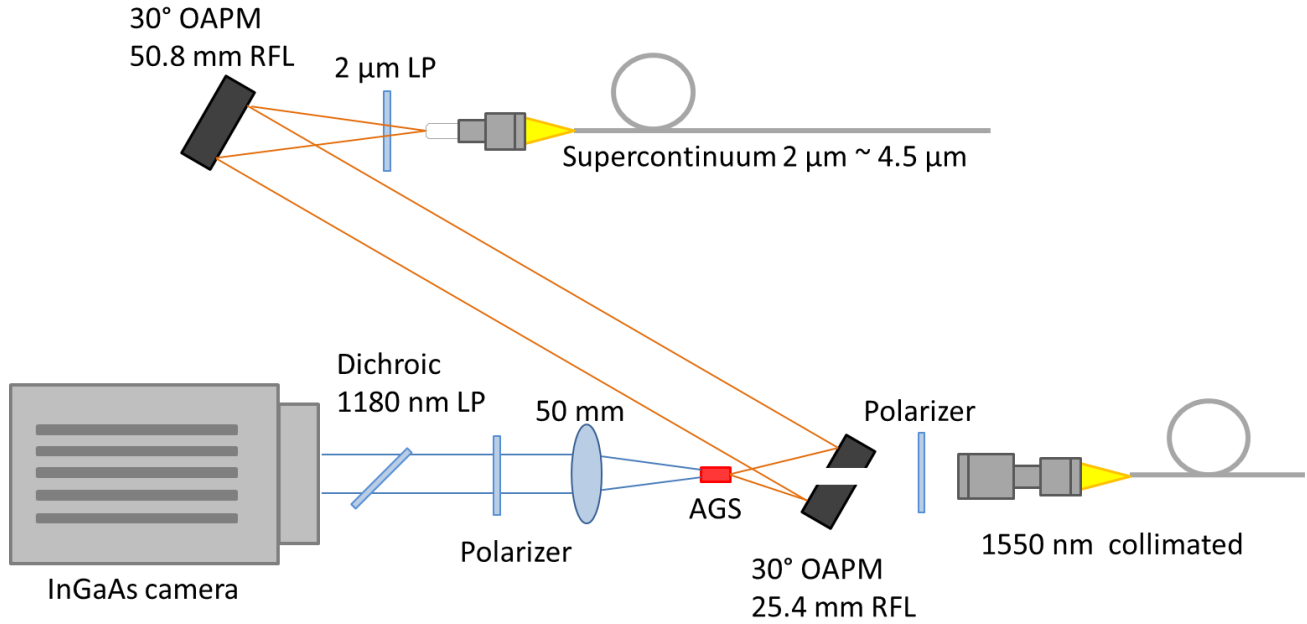


Figure 2: Top view schematic representation of the pulsed upconversion imaging setup. The use of OAPMs make for a mostly achromatic setup. The broadband signal pulse is combined with the 1550 nm pump pulse through a hole drilled through an OAPM.

very wide spectral band. This is particularly relevant in the infrared where designing reflection and transmission coatings operating across wide spectral bands can become a major challenge. It is important to choose mirrors with the smallest possible reflection angles. Indeed, while OAPMs offer excellent collimation, and point-focusing performances, the imaging process is hindered by the fact that the focal length of each sub-area of the mirror is different, resulting in lateral field distortion when used for imaging applications. Using parabolic mirrors designed for incidence angles closer to normal incidence reduces this effect. The pump arm is collimated to a 2.1 mm  $1/e^2$  diameter beam and is shone through a 3.3 mm diameter hole drilled at the center of the OAPM. The beams are superimposed inside a 5 mm x 5 mm x 10 mm AgGaS<sub>2</sub> crystal cut at 54°.

### 3. THEORY

The crystal is placed on a rotation stage to allow for angle tuning of the phase-matching condition. The sum-frequency generation process relies on type II phase-matching. The phase-matching scheme is illustrated in Fig. 3. As a result of the nonlinear process, the IR signal gets converted to the 1030 nm to 1155 nm range.<sup>10</sup> The IR signal, pump and upconverted signal wavelengths  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  respectively are linked by the relation stated in Eq. 1.

$$\frac{1}{\lambda_3} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \quad (1)$$

The relation between the mixing angles and the wavelengths is given by Eq. 2.

$$k_1^2 = k_2^2 + k_3^2 - 2k_2k_3\cos\theta_3 \quad (2)$$

In this equation  $k_1$ ,  $k_2$  and  $k_3$  represent the wavenumbers of wavevectors  $\vec{k}_1$ ,  $\vec{k}_2$  and  $\vec{k}_3$  which correspond to the input signal, the pump, and the upconverted signal respectively.

The upconverted plane waves exiting the crystal are then propagated through a simple 50 mm focal length plano-convex lens placed at 50 mm from the Fourier plane. The first lens is a 30 mm focal length plano-convex placed at 30 mm of the Fourier plane. In the focal image plane of this lens, the upconverted image is acquired on an Peltier-cooled InGaAs camera.

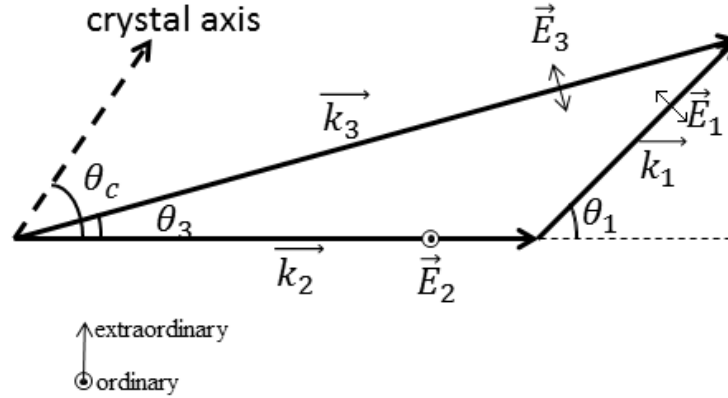


Figure 3: Type II phase-matching upconversion scheme.  $\vec{k}_1$ ,  $\vec{k}_2$  and  $\vec{k}_3$  represent the wavevectors of the input signal, pump, and upconverted signal respectively. The pump is polarized along the ordinary direction while the input signal and upconverted signal are polarized along the extraordinary direction

The quantum efficiency of the phase-matched light traveling along the center of the nonlinear crystal is calculated to be  $1.0 \times 10^{-4}$ .<sup>10</sup> The 2.1 mm  $1/e^2$  diameter of the pump beam is here the main parameter reducing the efficiency. Additionally, the source does not implement any polarization control, which causes a decrease in efficiency of a factor four. However, the high number of available IR signal photons allows the easy detection of an image on the camera. First, images were made without the resolution target. A consequence of the angular-dependent phase-matching condition seen from Eq. 2 is that different spectral components of the input IR light are upconverted at different angles. A bright spectral component in the object light will result in a bright ring in the image. Thus, the supercontinuum illumination will get upconverted as a series of adjacent rings, effectively forming a disc, ranging from shorter wavelengths in the center to longer wavelengths at larger radii. This distribution can be observed in Fig. 4. The phase-matching condition is highly dependent on the cut angle, rotation and temperature of the crystal. This is the property that can be exploited to reconstruct hyperspectral images by angle or temperature tuning of the crystal or by translating the sample.<sup>7</sup>

#### 4. RESULTS

A US Air Force 1951 resolution target is placed in the sample plane. Figure 5 shows upconverted images that were acquired with 75 ms exposure time. We can observe some lateral field distortion which is believed to be due to the use of OAPMs as discussed above. The smallest resolvable feature is 12.7 lines/mm which gives us a resolution of  $79 \mu\text{m}$ . If we consider that resolution is mainly limited by the diameter of the pump beam which acts as a soft aperture in the Fourier plane, we calculate that the theoretical resolution is approximately  $55 \mu\text{m}$ . The experimental and theoretical resolution are of the same order of magnitude, and the difference can be accounted for by the misalignment and aberrations of the optics in the setup. While the resolution can be tailored by changing the magnification of the optics, the number of resolvable elements is limited by the ratio of the area of the point-spread function over the total field of view, and this is thus more relevant for the characterization of upconversion imaging devices. The use of a pulsed source allows the use of 2.1 mm  $1/e^2$  diameter mixing pump diameter in the Fourier plane which thus leads to enhanced spatial resolution. Additionally, the broad spectral range of the source allows for a wide field of view of 14.9 mm in diameter. Taking into account the 3.3 mm diameter hole in the center of the image, this gives us approximately 32400 resolvable elements. Next, we place a sample cut out from a polypropylene drinking cup in the sample plane. The upconverted image gives us access to both the spatial information of the sample as well as information about the absorption spectrum of the material. On Fig. 6a we notice a dark ring that corresponds to an absorbing spectral feature of polypropylene. This feature corresponds to the stretching vibration bands of the  $\text{CH}_2$  and  $\text{CH}_3$  groups of the polymer as is shown in Fig. 6b.

In conclusion, we have demonstrated the first pulsed upconversion imaging system using a supercontinuum light source. A complex infrared signal in the  $3 \mu\text{m}$  to  $4.5 \mu\text{m}$  range was thus successfully upconverted to the

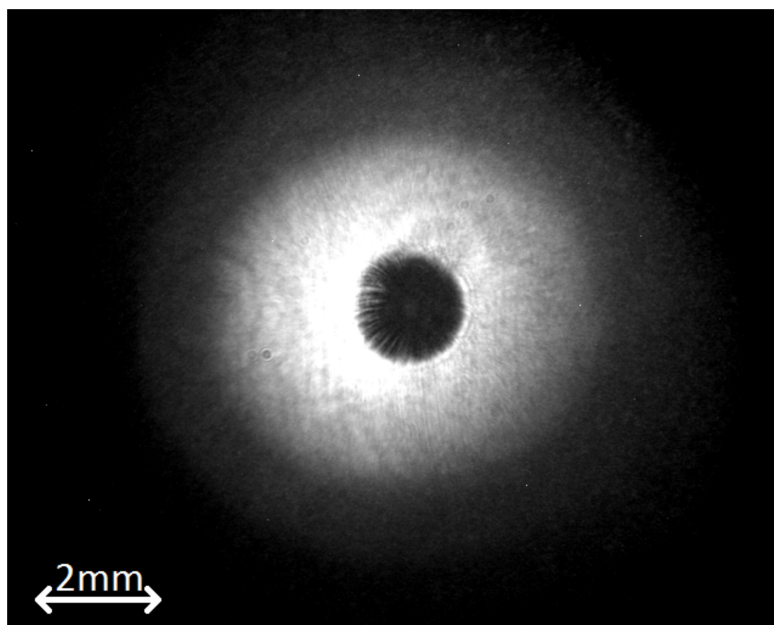


Figure 4: Raw upconverted image of supercontinuum illumination with 75 ms exposure time. Due to the phase-matched nature of the upconversion process, the upconverted wavelengths are distributed radially across the image plane. The hole in the center of the image is due to the hole in the mixing OAPM.

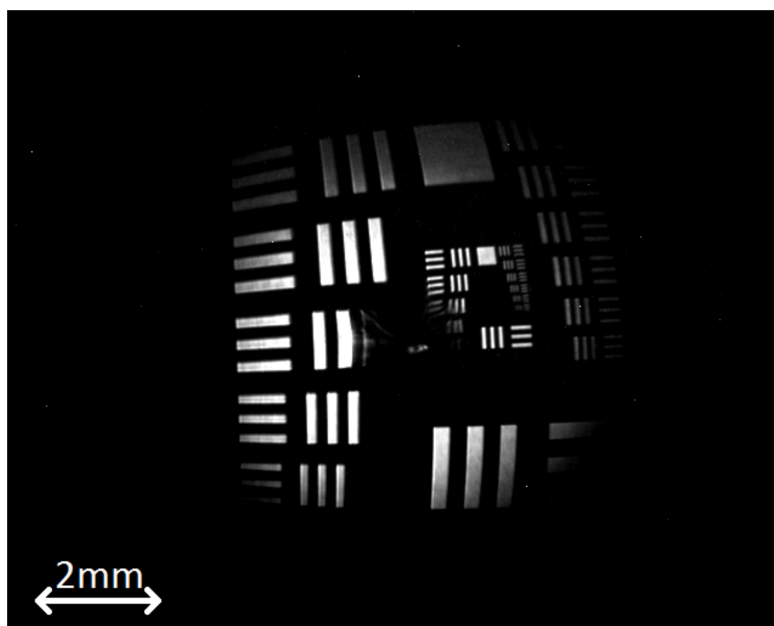


Figure 5: Upconverted transmission image of a USAF 1951 resolution test target with 75 ms exposure time. The smallest resolvable feature is 12.7 lines/mm. The image counts 32400 resolvable elements. The deformation of the features near the center of the image is due to the hole in the mixing OAPM.

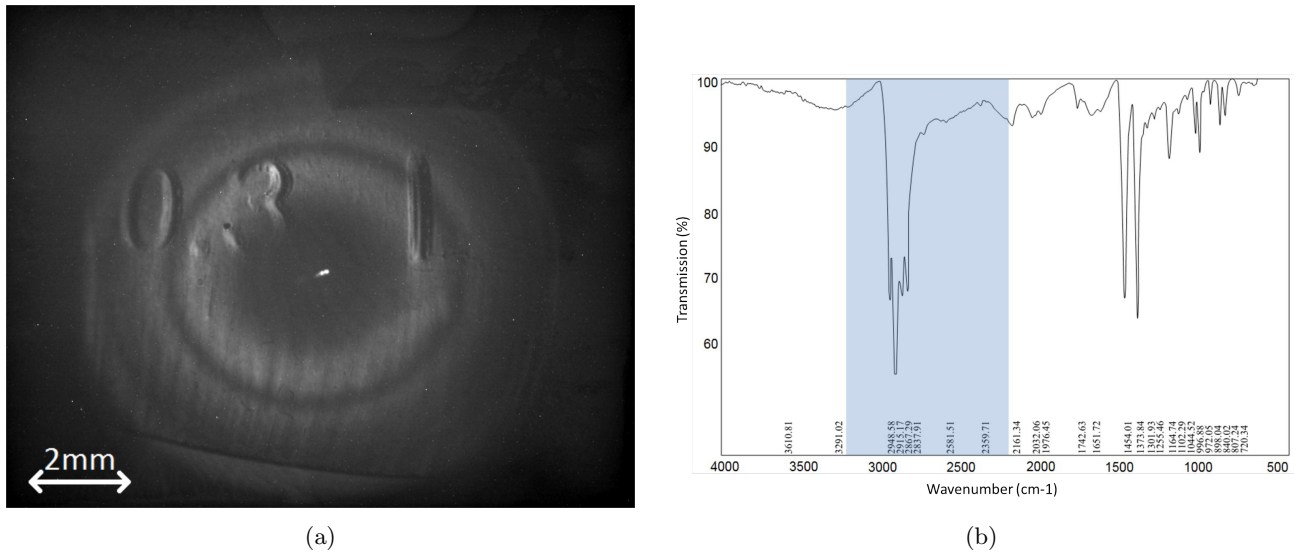


Figure 6: (a) Upconverted transmission image of a polypropylene drinking cup. We can observe both the spatial features of the characters printed on the cup as well as some spectral absorption features. The dark ring is due to strong absorption peaks of  $\text{CH}_2$  and  $\text{CH}_3$  bonds. (b) Infrared absorption spectrum of polypropylene. The blue area represents the probed wavelength region

1030 nm to 1155 nm range and acquired on a Peltier-cooled InGaAs camera with an acquisition time of 75 ms. Additionally, the use of the high brightness supercontinuum and the synchronous pulsed upconversion scheme drastically expands the choice of usable crystals. In this case, the use of a large pump beam diameter inside a bulk AgGaS<sub>2</sub> crystal has allowed us to obtain images with good spatial resolution.

As a consequence of the phase-matching condition, spectral components are upconverted in different parts of the image, which makes this system an interesting choice for spectroscopy and hyperspectral imaging applications. The fast acquisition time would make it suitable for on-line industrial vision applications, fast gas sensing and bio-medical imaging. Finally, this particular system has the advantage of being mostly achromatic. By choosing the nonlinear crystal appropriately, we can rely on a very similar system to perform pulsed upconversion imaging further in the infrared using novel long wavelength supercontinuum sources even further in the infrared.

## ACKNOWLEDGMENTS

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